SOLAR ENERGY AND ELECTRIC UTILITIES:
CAN THEY BE INTERFACED?

by

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August 1976

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ABSTRACT

This paper re-evaluates the economics of solar systems that
interface with electricity supply systems. First, adopting the implicit
assumption of many solar system designers of abundant supplies of low-cost
off-peak electricity, we undertake systems studies of several of the more
important solar energy applications. It is shown that much of the electricity
supply savings claimed for solar energy systems stem from the storage, rather
than the solar, component of the system. Second, employing a standard
economic representation of the periodic load problem, we examine the general
problem of interfacing solar energy and electric utility supply systems.

The general conclusion of the paper is that solar energy systems
and conventional electric utility systems represent a poor technological
match. The basic problem is that both technologies are very capital inten-
sive. The electric utility, because of the high fixed costs of generation,
transmission, and distribution capacity, represents a poor backup for solar
energy systems. On the other hand, the solar collection system, because it
represents pure, high-cost capital and because of the periodic nature of its
output, should not be considered as a part-load source of auxiliary energy
for the utility.

I. INTRODUCTION

A number of investigators have proposed solar energy systems that interface with conventional electric utility supply systems. Whether considering solar thermal conversion systems to produce electric utility power or solar systems for thermal applications in buildings, the systems' proponents have generally concluded that solar energy can reduce electric utility fuel and capital requirements. In both utility power system and utility customer end-use applications, solar energy saves fuel directly by substituting for utility fossil and nuclear fuels. Utility capital and indirect fuel savings occur as a result of the ability of the storage system, always included in the solar system design, to displace the solar system's auxiliary energy requirements to off-peak hours. The effect is to reduce the utility's peak-period loads from what would otherwise occur, thereby allowing the substitution of base-load plant and fuels for peak- and intermediate-load plant and fuels.

Recently, proponents of solar heating and cooling of buildings have emphasized that solar insolation outage can be covered entirely with inexpensive off-peak electric power (1). All that is required is the incorporation of a thermal storage system with capacity adequate to meet the design-day building load. What these proponents have failed to point out is that the inclusion of thermal storage effectively reduces the function of the solar collector component of the solar energy system to the displacement of off-peak electric energy. This fact greatly diminishes the economic benefits that can be attributed to solar energy systems.

It is the purpose of this paper to re-evaluate the economics of solar energy systems that interface with conventional electric utility supply networks. The re-evaluation proceeds along two paths. First, adopting the implicit assumption of many solar system designers of abundant supplies of

low-cost off-peak electricity, we undertake systems studies of several of the more important solar energy applications. Second, employing a standard economic representation of the periodic load problem, we examine the general problem of interfacing solar energy and electric utility supply systems.

A central theme of the systems studies is that solar energy systems are most logically compared with the storage-augmented versions of the conventional systems that they are designed to supplement or replace. Adopting this approach, we estimate solar collector breakeven costs for solar/electric-resistance and solar/heat pump systems for space heating and solar thermal conversion systems for electric power generation. For solar/electric-resistance heating, the upper bound on solar collector breakeven costs is found to be approximately $30/m^2 ($\approx$$3.00/ft^2) if auxiliary energy is from coal-fired utility generating plant and $75/m^2 if auxiliary energy is from oil-fired utility plant. For all the solar/heat pump configurations examined, the collector breakeven costs are found to be substantially lower than for the comparable solar/electric-resistance heating systems.

The general problem of interfacing of solar energy and electric utilities is treated by analyzing the economics of solar collection under two alternative scenarios. Under the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future. (This corresponds to the economists' "firm-peak" case.) Under the second scenario, either through the introduction of new technology or through time-of-use pricing, the utility's load curve becomes flat (shifting-peak case). For the first scenario, it is shown that solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than variable (fuel) cost component of off-peak electricity. For regions of the country where the utility off-peak fuel is coal or nuclear fuel, this implies very low solar collector breakeven costs. In

regions of the country where the cost of off-peak electricity is higher than other auxiliary energy forms -- the utility fuel is oil -- the most economical solar energy systems will not interface with the electric utility. For the second scenario, the economic benefits of solar collection in most applications are found to be approximately equal to the value of the displaced utility fuel, indicating breakeven points for solar collectors that are roughly equal to those under the first scenario.

The general conclusion of the paper is that solar energy systems and conventional electric utility systems represent a poor technological match. The basic problem is that both technologies are very capital intensive. The electric utility, because of the high fixed costs of generation, transmission, and distribution capacity, represents a poor backup for solar energy systems. On the other hand, the solar collection system, because it represents pure, high-cost capital and because of the periodic nature of its output, should not be considered as a part-load source of auxiliary energy for the electric utility. Viewed in this context, the low breakeven costs established for solar collector systems that interface with electric utilities are merely symptomatic of the problem of matching two technologies that in important respects may be incompatible.

Because of the paper's extensive use of the concept of solar collection breakeven costs, it is important from the beginning to point out that: (a) these costs are always calculated by directly comparing the capital and fuel requirements of conventional systems with those of solar systems providing services of comparable quality, and (b) therefore, breakeven-cost values, where presented in the paper, are dependent on the costs assumed for the conventional technologies, but (c) the qualitative conclusions reached in the paper are essentially independent of the exact breakeven-cost values. The study does not explicitly examine passive solar building concepts that modify and

reduce normal thermal load requirements, nor does it analyze intermittent solar concepts (for example, air conditioning systems without adequate backup to cover solar outages) for which there are no conventional counterparts. As shown below, the upper-bound breakeven costs of solar collection are effectively "pinned" to the value of off-peak utility fuel. By calculating breakeven costs in terms of current prices of off-peak utility fuel, we effectively have neglected: any price-distorting effects that may result from government tax or subsidy programs, the many environmental spillover benefits that are commonly associated with solar energy, fuel conservation benefits beyond those reflected in current prices of utility fuel, and the possibility of fuel price escalation beyond the general inflation rate over the lifetime of the solar system. In defense of the last assumption, it must be said that, although there recently have been substantial increases in the real prices of base-load utility fuels, there does not appear to be a sound basis for expecting such increases to persist into the future (2).

The balance of this paper can be approached in several ways. For the system designer, the system decompositions and comparisons presented in Sections II, III, and IV may be of interest. However, the reader more interested in the general solar/ utility interface problem than in the details of specific solar applications can skip directly to Section V after reading Section II.

II. SOLAR/ELECTRIC-RESISTANCE HEATING

The re-conceptualization necessary to properly assess solar heating systems that interface with conventional electric supply systems is shown in Figure 1. As the figure illustrates, instead of comparing the cost of the solar heating system including storage with the cost of the conventional heating system (as in Figure 1(a)), the solar system designer should compare the cost of the solar-supplemented storage heating system against the cost of the simple storage heating system (Figure 1(b)). In practice, the latter

Fig. 1. Comparisons Among Solar, Storage, and
Conventional Space Heating Systems

comparison will proceed only after the benefits of storage heating relative to direct heating have been determined (Figure 1(c)). It is our contention that most of the electricity supply savings claimed for solar energy systems stem from the storage, rather than the solar, component of the systems.

That storage heating systems are cost-effective in service areas supplied by winter peaking utilities is well established (3). A recent study indicates that the utility savings, mostly capital savings, exceed the thermal energy storage costs by a factor ranging from two to four (4). The important consideration for the design of solar systems is that, given a storage capacity adequate to meet the design-day heating load, it makes economic sense to add a solar collector system only to the extent that it is cost-effective to substitute solar energy for off-peak electric energy. This consideration establishes an upper bound on acceptable solar collection costs,

$$C < S \cdot E.$$
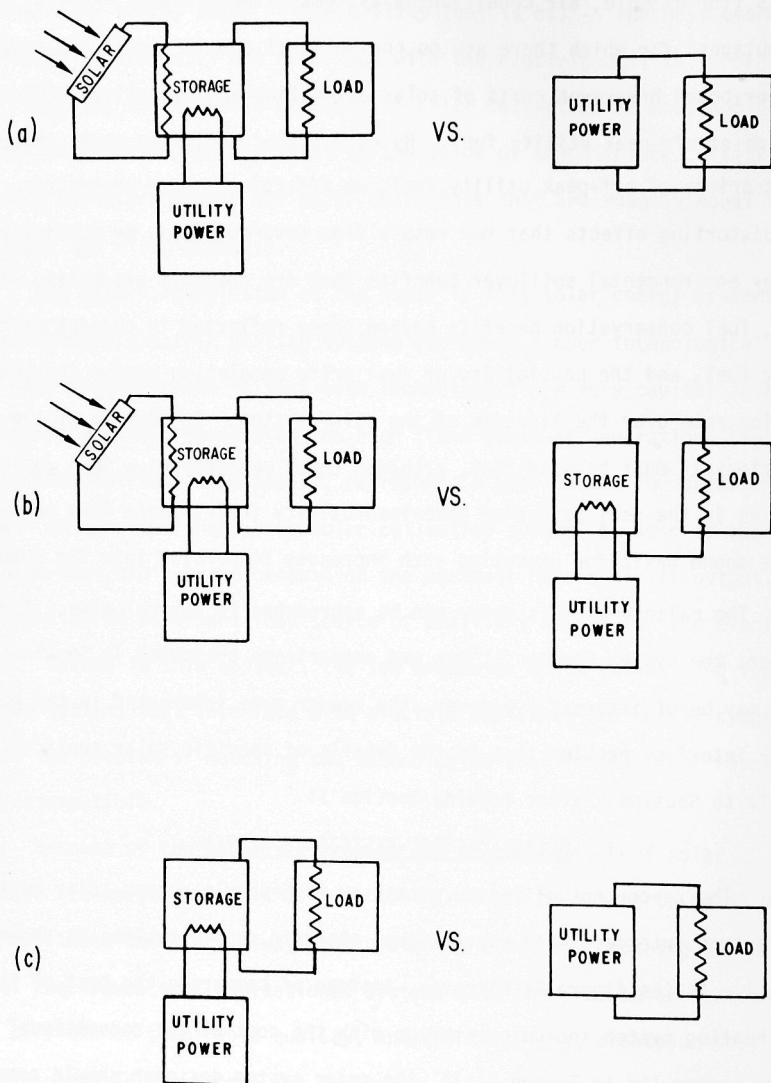
Here C equals the annualized cost ($\$/m^2/yr$) of the installed collector system (including the costs of piping, pumps, controls, heat exchanger, and the collector itself), S equals an upper limit on the amount of solar energy collected ($Kwh_t/m^2/yr$) and E is the cost of supplying off-peak electricity ($\$/Kwh_e$). For many regions of the country, a representative value for the cost of supplying off-peak energy is 10 mills per kilowatt-hour (= $\$0.01/Kwh$), which covers base-load fuel costs ($\approx \$1.00/10^6$ Btu) and base-load operating and maintenance costs. Under efficient cost allocation rules, all utility capital expansion costs should be charged against energy use during other time periods (5). An optimistic level of solar collection over the space heating season is 300 $Kwh/m^2/yr$ ($\approx$ 100,000 $Btu/ft^2/yr$). Because, for a fixed storage capacity, annual collection efficiency decreases with collector area, this

figure represents an upper limit on solar collection. Inserting these values for electricity cost and solar energy collection into the above relation, we obtain an upper bound on the breakeven cost of the solar collection system of $3.00/m^2/yr. If the real capital recovery rate is 10% per year, this corresponds to an upper bound on collector system costs of $30/m^2 ($\approx$ $3.00/ft^2). This is a very low breakeven value compared with estimates based on either the average or the peak-period cost of electricity supply. The upper bound on the breakeven cost is $75/m^2 if the auxiliary energy cost is 25 mills/Kwh.

In service areas supplied by summer peaking utilities, storage space heating generally is not cost-effective. In such service areas, the displacement of daily winter peak loads into nighttime valleys does not reduce the utility's annual peak capacity requirements. That, in this situation, the addition of a solar collector system could be cost-effective appears highly improbable. Having to support a sizable portion of the investment in the storage system, the return on the investment in the collector system will have to be higher than for the winter-peaking service area. The breakeven cost of the solar collector will be correspondingly lower and may even be negative.

Solar-assisted electric hot water heating may justify a higher collector cost than solar space heating. Solar hot water systems enjoy a better duty cycle, displacing off-peak electricity on a year round basis. On the other hand, solar hot water systems suffer a disadvantage relative to simple storage systems. This stems from the small additional cost of storage hot water heaters over conventional systems. Usually all that is required is a somewhat larger tank with improved insulation. The addition of a solar collection system, however, usually involves the addition of a separate preheat storage tank. A similar cost burden occurs in solar space heating applications when, in order to improve solar collection efficiency, separate storage systems are incorporated in both the solar supply loop and the backup electric supply system.

III. SOLAR ENERGY/HEAT PUMP SYSTEMS

Solar heating systems, more complex than the ones described above, have been proposed. In particular, the solar-assisted heat pump has received considerable attention (6). In one version of this system, the output of the solar collector is first input to a storage reservoir on the cold side of the heat pump (7). The solar energy is removed from the reservoir by the compressor action of the heat pump and is delivered to the building load.

The principal advantages of the solar-assisted heat pump are the lower temperature required for the output of the solar collector and the improved heat pump performance because of the solar warming of the input reservoir. According to the system's advocates, this allows the use of a much lower cost solar collector, thus improving the breakeven economics of solar heating. However, as shown below, another effect of incorporating a heat pump in the solar system design is to drive down the breakeven cost for the solar collection system.

The same techniques used in evaluating solar systems that interface with resistance heating can be used to analyze the solar-assisted heat pump design. Figure 2 presents a set of system comparisons building from direct resistance heating to the solar-assisted heat pump system. One of the steps in the system evolution in Figure 2 represents an inferior progression and has been included only to facilitate the analysis. The system incorporating a heat pump in Figure 2(b) is inferior to the system without a heat pump.

The heat pump operating solely off the electrically augmented storage on the input side is deficient on a number of counts. Because the heat pump can extract no more energy from the storage than is input, supplemental off-peak electricity is more efficiently stored and recovered in the system on the right hand side of Figure 2(b) where no work of compression is involved. The heat pump system is also more capital intensive, requiring a higher initial customer
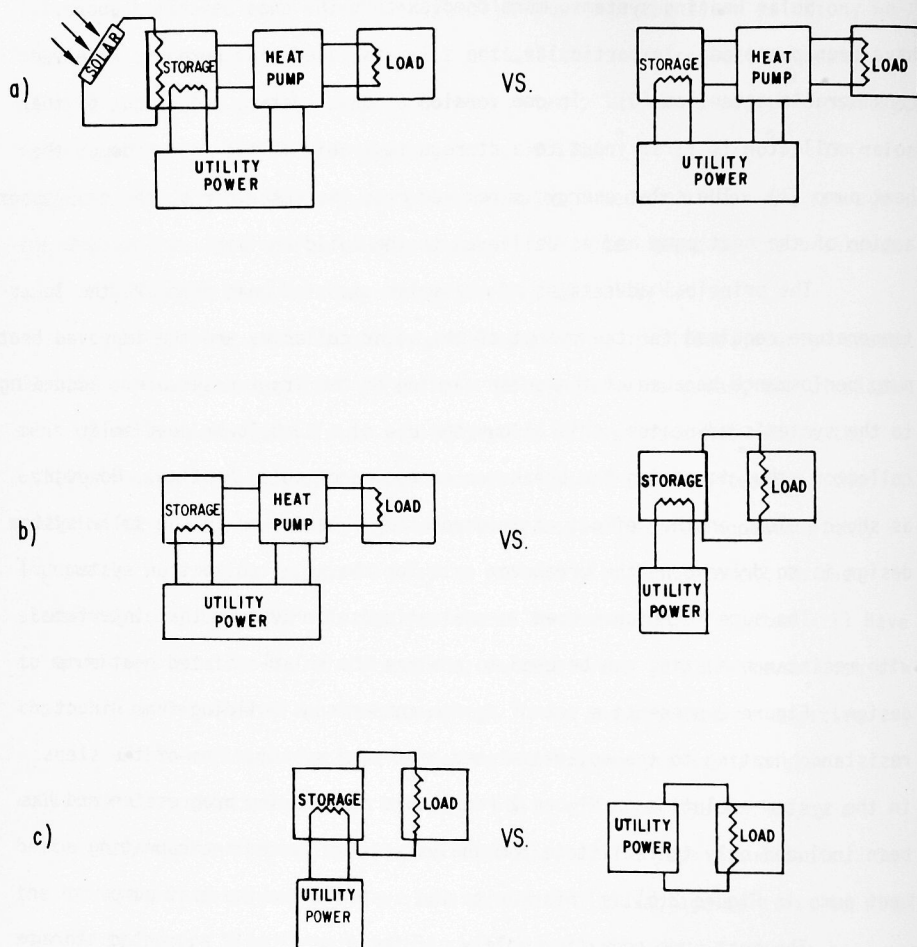
Fig. 2. Comparisons Among Solar-Assisted Heat Pump,
Storage, and Conventional Space Heating Systems

investment and greater utility capacity to meet the heat pump's contribution to the utility's daily peak load. As will become clear below, the inclusion of the heat pump with an electrically augmented input reservoir in Figure 2 is simply part of a "gedanken" experiment to determine the overall cost-effectiveness of the solar-assisted heat pump system.

The system comparison in Figure 2(a) lends itself to a particularly simple interpretation of the role of the solar collector subsystem. For purposes of comparison, the system on the right hand side of the figure can be conceived as operating in a fashion almost identical to its solar counterpart, the only difference being that the electrical energy is input to the right hand storage reservoir during off-peak nighttime hours while the solar energy is input to the left hand reservoir during daytime hours. Although, as described above, this use of electricity is extremely inefficient, it amounts to no more than a simulation of the use of the solar energy that is input to the solar system.

Viewed in this context, the gross benefit from the addition of the solar collector to the heat pump system is no greater than the benefit realized when a solar collector is added to a solar-resistance heating system, namely the displacement of off-peak electric energy. However, now the gross benefit also must cover (relative to the solar-resistance system): the added capital cost of the heat pump over the resistance system, the utility capital costs associated with the supply of electricity to the heat pump during on-peak hours, and the cost of utility energy to run the heat pump. For the fraction of time when solar energy is not available, the heat pump can run off ambient air. This does not alter the relative economics of the solar-assisted heat pump and the storage heat pump in the Figure 2(a) comparison, because both systems would benefit equally from this option. However, it would reduce the heat pump cost burden slightly by the amount of the additional off-peak electricity displacement credit.

The additional capital cost of the heat pump system relative to the resistance system, after an air conditioner capital cost credit, is approximately $1000 (8,9). For a nominal collector area of $50m^2$, this corresponds to a reduction relative to the breakeven point for the collector subsystem in the solar/resistance system of $20/m^2$. In a service area supplied by a winter peaking utility, a more significant cost penalty is the utility capital cost of meeting the design-day compressor load (10). This cost, covering utility demand-related capital expansion costs at the generation, transmission, and distribution levels amounts to approximately $500 per peak kilowatt, corresponding to $2000 for the heat pump and $40/m^2$ for the $50m^2$ collector. The breakeven point is then -$30/m^2$ if auxiliary energy costs are 10 mills/kWh and $15/m^2$ if auxiliary energy costs are 25 mills/kWh.

In a service area supplied by a summer peaking utility, utility winter peak-day capacity costs are considerably lower, depending upon such considerations as reserve margin under scheduled maintenance outage. However, even if utility power costs are assumed to be negligible, the breakeven point for the solar collector component of the solar-assisted heat pump system will be lower than that of the solar/electric-resistance heating system by the amount of the added capital cost of the heat pump.

Another solar-energy/heat-pump design concept is illustrated in Figure 3. Here, the storage reservoir is on the "hot" side of the heat pump and both the solar collector and the heat pump deliver energy directly to the reservoir. In analyzing this system, we shall first discuss the trade-offs involved in adding a heat pump to a storage resistance heating system [Figure 3(b)] and then the economics of adding a solar collection system to the heat pump storage system [Figure 3(a)].

The comparison of the storage heat pump system on the left hand side of Figure 3(b) with the simple storage resistance heating system indicates that the heat pump can reduce annual energy consumption by the factor [1 - ....],
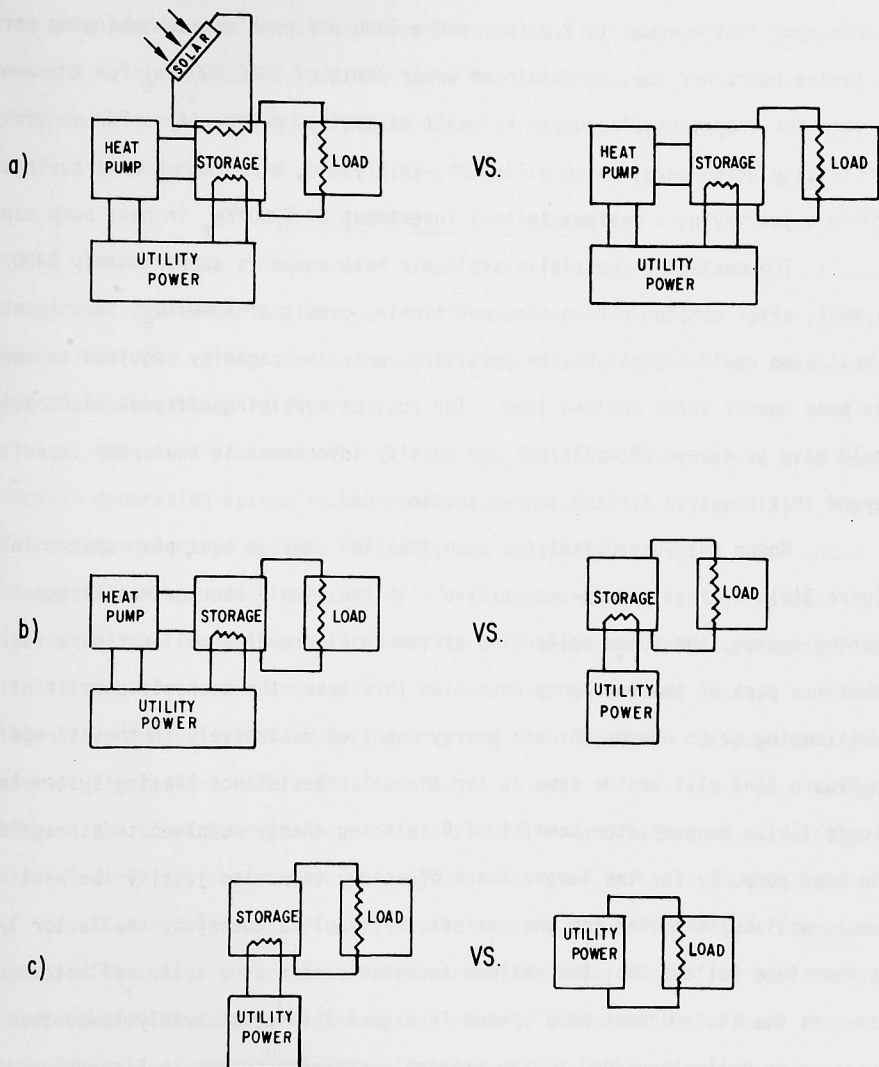
Fig. 3. Comparisons Among Solar/Heat Pump, Storage,
and Conventional Space Heating Systems

where $\bar{F}$ is the average seasonal performance factor over the winter heating season. Assuming an annual heating season of 4000 hours, an optimistic seasonal performance factor equal to 2.0 (8), and a long off-peak storage charging period of twelve hours per day, we obtain an upper limit of 2000 Kwh/Kw$_e$ for the amount of off-peak energy displaced per kilowatt of heat pump capacity. For an off-peak electricity price equal to 10 mills/Kwh, this yields a maximum annual savings of $20/Kw$_e$, justifying a maximum initial investment of $200/Kw$_e$ in heat pump capacity.

The cost of commercially available heat pumps is approximately $400/Kw$_e$ so that, after netting out an air conditioning credit of $200/Kw$_e$, investment in a heat pump could conceivably be justified up to the capacity required to meet the peak summer space cooling load. The cost of supplying off-peak electricity would have to exceed 20 mills/Kwh$_e$ to justify investment in heat pump capacity beyond that required for the summer cooling load.

Under the very optimistic case that the storage heat pump system in Figure 3(b) is exactly cost-competitive with the simple storage resistance heating system, the solar collection system in Figure 3(a) will not have to subsidize part of the heat pump cost. In this case, the economic benefit of substituting solar energy for any energy supplied resistively to the storage in Figure 3(a) will be the same as for the solar/resistance heating system in Figure 1(b). However, the benefit of displacing energy supplied to storage by the heat pump, by far the larger share of energy (how else justify the heat pump), will be less than for the resistively supplied energy by the factor $1/\bar{F}$. It therefore follows that the maximum acceptable cost of a solar collector added to the storage heat pump system in Figure 3 is considerably lower than for a solar collector added to the storage resistance system in Figure 1.

Although the foregoing analyses have been limited to two generic types of solar-energy/heat-pump systems, the conclusions reached appear to be generally

applicable to all types of solar/heat pump systems. Our analyses of other types of heat pump concepts indicate that they can always be evaluated by decomposition into some combination of the solar/resistance-heating and the two solar/heat-pump concepts described above. All the solar/heat-pump concepts that we have identified have breakeven solar collection costs considerably lower than the breakeven solar collection costs of the solar/resistance-heating system in Figure 1.

IV. SOLAR ELECTRIC POWER GENERATION

Many of the same kinds of trade-offs affecting the economics of solar energy applications in buildings affect the economics of solar electric power generation. Figure 4 presents the solar electric analogues of the heating-system comparisons presented in Figure 1.

The usual procedure for determining the cost-effectiveness of a solar electric generating system is the comparison indicated in Figure 4(a). The cost of the solar electric system, including any necessary backup to cover solar outage, is compared with the cost of the conventional generating system. In Figure 4(a) the comparison is presumed to be between the solar system including its backup boiler and a conventional intermediate generating plant. (To facilitate later analysis, a base-load generating plant has been included on both sides of Figure 4(a). This facility "cancels out" in the Figure 4(a) comparison.) Although the comparison in Figure 4(a) is the standard method of evaluating solar electric systems, a more meaningful comparison is that shown in Figure 4(b).

That a solar electric system can survive comparison with a storage-augmented base-load generating plant is very doubtful. Given low cost storage, a storage-augmented base-load plant can replace a combination of base and intermediate (or peaking) plants. (See Figure 4(c).) In a recent study, Public Service Electric and Gas Company (11) calculated breakeven costs for thermal storage in this application at $630/Kw (10 hour storage device) and $350/Kw (5 hour

B = BASE BOILER   R = SOLAR RECEIVER   G = GENERATOR

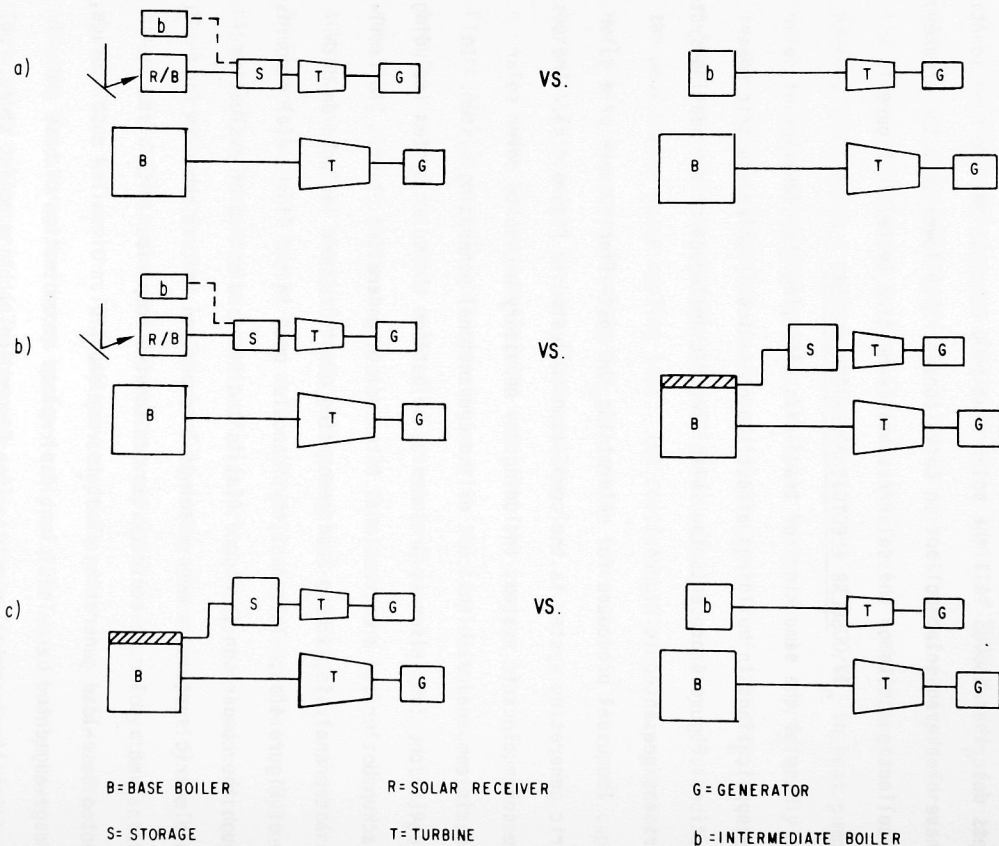S = STORAGE   T = TURBINE   b = INTERMEDIATE BOILER

Fig. 4.   Comparisons Among Utility Solar Thermal Conversion,
Thermal Storage, and Conventional Power Generation

storage device) (12). On the other hand, in the Figure 4(a)-type evaluation of the economics of solar electric power systems, the Aerospace Corporation (13) assumed solar storage device costs several times lower than the PSE&G storage breakeven costs. For the most attractive solar electric application examined in the Aerospace study (central station receiver plus 6-hour storage vs. intermediate generating plant), the heliostat effective breakeven cost was about $30/m^2$. Already a difficult cost objective to achieve, the breakeven cost would have been considerably lower if the solar electric system had been compared against a storage-augmented base-load generating plant.

V. GENERALIZATION AND SUMMARY

The preceding analysis was limited to those types of solar systems that interface with electricity supply systems. In considering such systems, the analysis stressed the low breakeven costs of solar collection systems whose only effect is to substitute solar energy for low cost off-peak electricity. The question naturally arises as to how the breakeven economics would be affected by the absence of low cost off-peak electricity.

In an important sense, off-peak electric power is merely a by-product of on-peak electricity. However, its future availability might very well diminish as utilities and regulators begin to price it at cost and customers respond by purchasing it in increasing quantity. The European experience indicates that, given adequate customer price incentives, the time required for complete "valley filling" for a winter peaking utility system can be as short as 10 to 15 years (2). Therefore, to complete our analysis of solar energy systems that interface with electric utility systems, we shall try to generalize our results by considering two alternative scenarios. Under the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future; under the second

scenario, as a result of the introduction of a new technology or the implementation of some form of peak-load pricing, the utility's load curve becomes flat.

Under the first scenario, in most parts of the country off-peak electricity will remain the lowest cost auxiliary energy available for solar energy systems. Systems that use this form of auxiliary energy will represent the economically (and socially) most efficient solar energy systems. Thus, to be economical, solar collection systems will have to be low enough in cost to supply solar energy that is cost-competitive with off-peak electricity.

Even under the first scenario, there may remain, as there are today, many utility service areas where off-peak electricity is not the lowest cost source of auxiliary energy. Today, many utilities use oil in base-load generating plant, with the cost of the oil approximately $87 per metric ton ($13/bbl). After correction for transmission and distribution losses, this gives a cost of approximately 25 mills/Kwh ($8.40/$10^6$ Btu). On the other hand, the price of home heating oil currently is about 11¢/liter (42¢/gallon), which after correction for furnace conversion efficiency is equivalent to approximately 15 mills/Kwh ($5.00/ 10^6 Btu). Thus, in service areas supplied by utilities using oil-fired base-load plant, fuel oil may represent the lowest cost auxiliary energy form. Although natural gas can also be used to supplement solar systems, its price (marginal cost) under national deregulation is likely to be somewhat higher than the price of oil.

To summarize, the findings for the scenario involving indefinitely available low cost off-peak electricity are as follows: In those service areas supplied with electricity from coal or nuclear generating plants, the most economical solar energy systems will be those that use off-peak electricity as the auxiliary energy source. Accordingly, solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than

the cost of off-peak electricity. As we have already seen, the upper limit
on breakeven costs is about $30 per square meter of collector area. In
service areas supplied with off-peak electricity produced from expensive fuels,
such as oil or natural gas, the most economical solar energy systems will be
those that utilize auxiliary fuels other than off-peak electricity. In these
service areas the most economical solar systems will not interface with the
utility supply system.

To analyze solar energy breakeven economics under the second scenario,
we shall have recourse to a standard economic representation of the periodic load
problem (14). We shall first examine the special case that the load becomes
flat under a uniform price over the utility's entire demand cycle. Conceivably
this might occur as a result of the large-scale introduction of another new, but
non-solar, technology. (For example, the electric vehicle.) The energy demand
associated with the new technology, would have to be concentrated during what
otherwise would be off-peak hours and be of the proper magnitude and temporal
distribution to equalize the rates of consumption during each subperiod of the
demand cycled. Although unlikely to occur in practice, we shall examine this
special case as a heuristic step toward the more general case involving a
uniform load brought about by the introduction of inter-period price differen-
tials.

Figure 5 captures the essential elements of the uniform-load,
constant-price problem. The curve D_E represents the demand for electricity over
the entire demand cycle for the case without the addition of a solar collector
system. This curve, which presents a uniform load over the entire demand cycle,
intersects the supply-cost line $b + \beta$ at point A, corresponding to a capacity
requirement without solar equal to Q. The part of the demand curve D_e lying
above the short run marginal (fuel) cost curve b represents the "effective

Fig. 5. Electricity Supply/Demand Relations for
Cases With and Without Solar Supplement;
Uniform Load, Constant Price
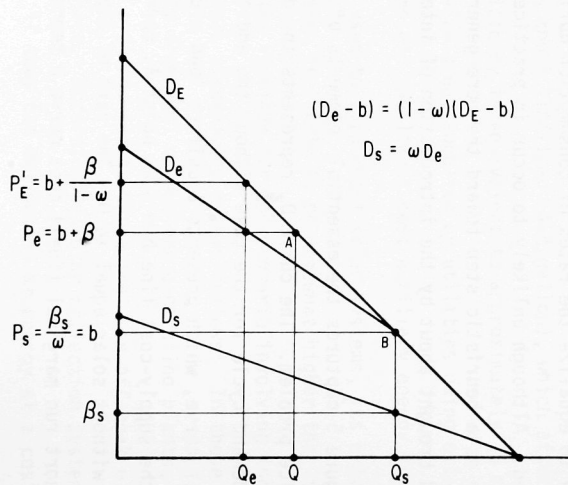
D_E = DEMAND FOR ENERGY

$(D_e - b)$ = DEMAND FOR ELECTRIC CAPACITY

D_s = DEMAND FOR SOLAR CAPACITY

b = ELECTRIC UTILITY FUEL COSTS (¢/KW-cycle)

β = ELECTRIC UTILITY CAPITAL EXPANSION COSTS (¢/KW-cycle)

β_s = SOLAR CAPITAL EXPANSION COSTS (¢/KW-cycle)

Q = ELECTRIC CAPACITY W/O SOLAR (KW)

Q_e = ELECTRIC CAPACITY WITH SOLAR (KW)

Q_s = SOLAR CAPACITY (KW)

P_e = ELECTRICITY PRICE W/O SOLAR (¢/KW-cycle)

P_e' = ELECTRICITY PRICE WITH SOLAR (¢/KW-cycle)

P_s = SOLAR ENERGY PRICE (¢/KW-cycle)

$(D_e - b) = (1 - \omega)(D_E - b)$

$D_s = \omega D_e$

$P_E' = b + \dfrac{\beta}{1 - \omega}$

$P_e = b + \beta$

$P_s = \dfrac{\beta_s}{\omega} = b$

demand for capacity" for the case with solar and is equal to $(1 - \omega)(D_E - b)$, where ω is the fraction of demand cycle during which electricity is displaced by solar energy. In the limit that ω approaches zero, the curve D_e coincides with D_E. The demand for solar energy is represented by the curve D_s. For the fraction of the cycle that solar supplies the load, fuel costs are zero, so that the demand for solar capacity is given by $D_s = \omega D_E$.

As indicated in the figure, one of the effects of the addition of the solar collection system is to reduce the optimum electric generating capacity from Q to Q_e. Another effect is to increase the price of electricity from $P_E = b + \beta$ to $P_e = b + \beta/(1 - \omega)$. That the price P_e exactly covers costs for the solar case is easily verified from the revenue relation: $R = (1 - \omega)Q_e P_e = Q_e[(1 - \omega)b + \beta]$, where the first term in brackets equals electric variable costs and the second term equals electric capital costs.

Just as the optimum electric capacity is given by the intersection of the electric demand and supply curves, the optimum solar system capacity is given by the intersection of D_s with the solar supply cost curve β_s/ω. In Figure 5 the intersection occurs at the point B, corresponding to an optimum solar capacity equal to Q_s. Although the solar supply curve in Figure 5 has been set equal to b to coincide with the level of electric fuel costs, this need not be the case. The solar supply curve may be higher or lower than b, depending upon the unit cost, β_s, of solar capacity and the fraction of time, ω, that solar supplies the load. The unit capital cost β_s includes the capital cost of the storage required for solar to supply ω-fraction of the cycle.

One of the interesting features of the efficient-price solution in Figure 5 is that the electric and solar capacities, Q_e and Q_s, are not necessarily equal. In fact, for P_s less than P_e, Q_s is always greater than

Q_e. In practice, however, the electric and solar capacities are likely to be set equal in order to satisfy capacity constraints imposed by the "downstream" facilities receiving energy from the two systems. Although the efficient (welfare-maximizing) solution for the constant demand case may call for a greater rate of energy supply during the solar part of the cycle, the need to expand the capacity of facilities that transport and use this energy and the underutilization of this capacity during the electric part of the cycle is likely to prevent this development.

The welfare implications of the addition of the solar collection system can be estimated by comparing welfare for the case without solar with the level of welfare after the addition of the solar collection system. The traditional definition of the social welfare function (consumers' surplus plus total revenues less total costs) leads to the following welfare relation for the case without solar

$$W = \int_0^Q P(q)dq - \beta Q - bQ.$$

Taking the derivative of this equation with respect to Q and setting the resulting expression equal to zero gives the welfare-maximizing price of electricity for the case without solar: $P_e = b + \beta$. The welfare function for the case involving solar is

$$W' = (1 - \omega) \int_0^{Q_e} P(q)dq - \beta Q_e - (1 - \omega)bQ_e + \omega \int_0^{Q_s} P(q)dq - \beta_s Q_s.$$

If there are no inter-period demand dependencies, we can set the partial derivatives of this function, first with respect to Q_e and then with respect to Q_s, equal to zero to obtain the efficient-price solutions for the case with solar: $P_e = b + \beta/(1 - \omega)$ and $P_s = \beta_s/\omega$.

Under the constraint that solar capacity equal electric capacity,
$Q_e = Q_s = Q^*$, the price solution can be obtained by setting the partial
derivatives of $W' - \lambda(Q_e - Q_s)$ equal to zero and solving the two simultaneous
equations for $P(Q^*)$. This gives

$$P(Q_e) = P(Q_s) = P(Q^*) = b + \beta + (\beta_s - \omega b).$$

It can be seen from this relation that if the cost of solar capacity per unit
of solar output exactly equals the price of the displaced utility fuel (that
is, $\beta_s/\omega = b$), then the price of energy with solar collection is equal to the
price without solar collection. Moreover, it is clear from the above relations
for W' and W, that if $Q_e = Q_s$ and $\beta_s/\omega = b$, then $W' - W = 0$.

If the cost of solar capacity β_s/ω falls either above or below the
price of the displaced utility fuel, the change in welfare will not be zero,
even under the constraint that $Q_e = Q_s = Q^*$. To see this we only need examine
the behavior of the derivative of W' with respect to ω.

$$\frac{\partial W'}{\partial \omega} = Q^* \left[b - \frac{\partial \beta_s}{\partial \omega} \right].$$

Clearly, only for the case that $\beta_s/\omega = b$ will W' not depend on the fraction ω
of the cycle supplied by solar energy. This finding combined with the earlier
result that $W' = W$ if $\beta_s/\omega = b$ means that the benefit of solar collection is
exactly equal to the value of displaced utility fuel. For $\beta_s/\omega < b$, the
benefit of installing a solar collection system is greater than the value of
the displaced fuel. On the other hand, the benefit is less than the value of
the fuel if $\beta_s/\omega > b$. The important conclusion is that the breakeven point
for solar collector costs under the constant-price, uniform-load case is the
same as for the peak/off-peak case analyzed above.

As emphasized above, the establishment of a flat load curve under a constant electricity price is very unlikely. A more plausible way for utility load curves to become flat is through the implementation of some form of peak-load pricing (higher rates during high-demand subperiods than during low-demand subperiods). Figure 6 illustrates Williamson's price solution for the two-subperiod case (15). The intersection of the effective demand for capacity curve D_e with the long-run supply cost line $b + \beta$ determines the optimum capacity Q for the case without solar. The high-demand subperiod price P_{e1} and the low-demand subperiod price P_{e2}, defined as the intersection of the vertical line through Q with D_1 and D_2, respectively, are "efficient" in the sense of maximizing consumer welfare. Moreover, it is readily verified that the prices are such that total utility revenues exactly equal total utility costs (16).

The effective demand for capacity D_e' for the case with solar is constructed under the assumption that solar outage is made up entirely by auxiliary electric energy supplied during the low-demand subperiod. As indicated in the figure, the effect of the addition of the solar collection system is to increase the price of electricity during each subperiod and to reduce the optimum utility capacity from Q to Q_e. By direct extension of the calculation for the single-period, uniform-price case, we can write the analytical expression for the welfare function W' for the case involving solar

$$W' = \omega_1 \int_0^{Q_e} P_1 \, dq + \omega_2' \int_0^{Q_e} P_2 \, dq - \beta Q_e - \omega_1 b Q_e - \omega_2' b Q_e$$

$$+ \omega \int_0^{Q_s} P_2 \, dq - \beta_s Q_s \, .$$

where $\omega_2' = \omega_2 - \omega$ equals that part of the second subperiod, expressed as a fraction of the entire demand cycle, that electricity continues to supply the load.

$$(D_e - b) = \omega_1 (D_1 - b) + \omega_2 (D_2 - b)$$
$$(D_e' - b) = \omega_1 (D_1 - b) + (\omega_2 - \omega)(D_2 - b)$$
$$D_s = \omega D_2$$
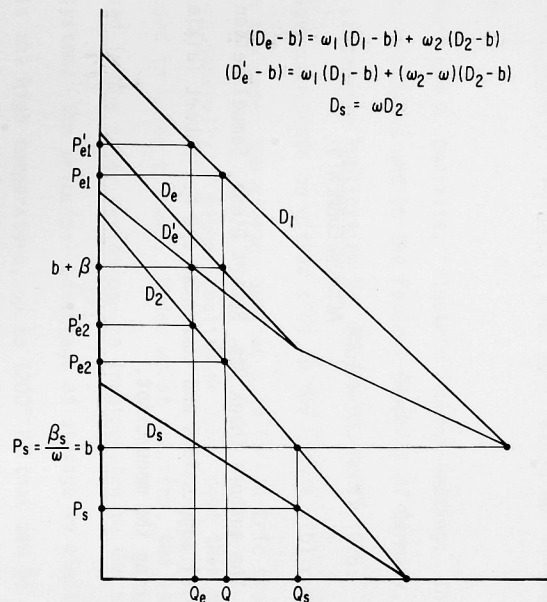
D_1 = DEMAND FOR ENERGY, PERIOD 1

D_2 = DEMAND FOR ENERGY, PERIOD 2

$(D_e - b)$ = DEMAND FOR ELECTRIC CAPACITY W/O SOLAR

$(D_e' - b)$ = DEMAND FOR ELECTRIC CAPACITY WITH SOLAR

D_s = DEMAND FOR SOLAR CAPACITY

ω_1 = FRACTION OF DEMAND CYCLE REPRESENTED BY PERIOD 1

ω_2 = FRACTION OF DEMAND CYCLE REPRESENTED BY PERIOD 2

ω = FRACTION OF DEMAND CYCLE SOLAR SUBSTITUTES FOR ELECTRICITY

P_{e1} = ELECTRICITY PRICE, PERIOD 1 W/O SOLAR

P_{e2} = ELECTRICITY PRICE, PERIOD 2 W/O SOLAR

P_{e1}' = ELECTRICITY PRICE, PERIOD 1 WITH SOLAR

P_{e2}' = ELECTRICITY PRICE, PERIOD 2 WITH SOLAR

P_s = PRICE FOR SOLAR ENERGY

Q = ELECTRIC CAPACITY W/O SOLAR

Q_e = ELECTRIC CAPACITY WITH SOLAR

Q_s = SOLAR CAPACITY

Fig. 6. Electricity Supply/Demand Relations for
Cases With and Without Solar Supplement;
Two Period, Non-Uniform Price

Imposing the constraint $Q_e = Q_s = Q^*$, we can deduce, following the same reasoning used above, that the change in welfare from the introduction of solar is zero, if $\beta_s/\omega = b$. It follows directly that $(W' - W) > 0$, $= 0$, or < 0, depending upon whether $\beta_s/\omega < 0$, $= 0$, or > 0.

The general conclusion following from the foregoing analyses is that solar energy systems that interface with electric utilities at best can be justified only in terms of the value of the off-peak utility fuels that they displace. For regions of the country where off-peak electricity costs are low, the most economically efficient solar energy systems will be those that use electricity as the auxiliary energy source. This has been shown to imply extremely low breakeven costs for a number of important solar energy applications. In regions where the cost of off-peak electricity is higher than that of competing energy forms the most economical solar energy systems will utilize auxiliary fuels other than electricity.

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   at Sharing the Sun Conference, Winnipeg, Canada, August 1976. See also
   "LILCO and Sunergy to Shift Load In Solar/Off Peak Electric System",
   article in Solar Engineering Magazine, August 1976, p. 24-25.

2. Basing the breakeven cost for the solar collection system on the current
   price of base-load fuel is equivalent to assuming that the real rate of
   increase of the price of base-load fuel less the real time rate of discount
   of money is zero. This appears to be a reasonable assumption. See, for
   example: Staff Report, Executive Office of the President, Council on
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   in the Midwestern Market," 1976 Industrial Power Conference, American
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3. J. G. Asbury and A. Kouvalis, "Electric Storage Heating: The Experience
   in England and Wales and in the Federal Republic of Germany," Argonne
   National Laboratory Publication No. ANL/ES-50, April 1976. Although
   the storage components on either side in the Figure 1(b) comparison
   are drawn the same, the storage devices used in electric storage heating
   systems are generally of higher quality or lower cost than the storage
   devices used in solar systems. Under worst practice, the same storage
   device used in the solar system can be incorporated in the storage
   heating system. The principal advantage of storage in electric storage
   heating is the high temperature, up to 1200° F, that can be achieved in
   magnesite bricks or other materials.

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7. See, for example: V. D. Karman, T. L. Freeman, and J. W. Mitchell, "Simulation Study of Solar Heat Pump Systems," presented at Sharing the Sun Conference, Winnipeg, Canada, August 1976, and references therein.

8. Gordian Associates Incorporated, "Evaluation of the Air-to-Air Heat Pump for Residential Space Conditioning," prepared for FEA (Contract No. FEA-CO-04-50171-00), April 1976.

9. As shown in Reference 8, the cost of a heat pump sized to meet the cooling load is approximately $1000 greater than the cost of an air

conditioner. This cost difference holds approximately for most regions of the country. Although the heat pump is less efficient in the air conditioning mode than the standard air conditioner, this charge against the heat pump is ignored here. None of the solar-assisted heat pump concepts considered here use solar energy when the heat pump is operating as an air conditioner.

10. We ignore the resistance component of the heat pump's design-day power demand. For the system design concept examined here, energy can in principal be input to the storage reservoirs during nighttime hours to eliminate the following day's on-peak resistance power requirement.

11. Public Service Electric and Gas Company, "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities," prepared for ERDA (Contract No. E(11-1)-2501) and EPRI (Research Project 225), December 1975.

12. These breakeven storage costs correspond to PSE&G's "typical values" for generating plant capital and fuel costs. PSE&G also calculated breakeven cost ranges corresponding to variations in input costs. The PSE&G "typical value" conventional-plant generating costs are similar to those used in the Aerospace study cited below.

13. The Aerospace Corporation, "Solar Thermal Conversion Mission Analysis - Southwestern United States," prepared for NSF (Contract No. NSF-C797), January 1975.

14. O. Williamson, American Economic Review 56, 810 (1966); M. Crew and P. Kleindorfer, Journal of Political Economy 79, 1369 (1971).

15. Williamson in his analysis explicitly assumes that the peak and off-peak period demands are independent of one another. In situations involving storage, this assumption is clearly invalid. However, for the constant load curve, the constraint $Q_1 = Q_2$ at the point of intersection of D_e with the long run cost curve b + β effectively removes the indeterminancy.

16. By adopting the Williamson efficient price solution, we have simplified the analysis by assuming only one type of utility generating plant. However, more detailed analyses, allowing several types of generating plant, usually yield off-peak generating costs only slightly different from those calculated using the Williamson method. (See Ref. 4.) Moreover, transmission and distribution capacity costs, which are a large component of residential supply costs, conform to the single-plant model.

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